

# **ECOCAR 3 INTERCONNECT DEFINITIONS, DESCRIPTIONS AND JUSTIFICATIONS**

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Presented to  
The Academic Faculty

by

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# **ECOCAR 3 INTERCONNECT DEFINITIONS, DESCRIPTIONS AND JUSTIFICATIONS**

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*To my team who made this possible,  
and my mother who helped me along the way.*

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## **LIST OF ABBREVIATIONS AND UNITS**

A	Ampere
ANL	Argonne National Laboratory
BMS	Battery Management System
CAN	Controller Area Network
DC	Direct Current
DTC	Diagnostic Trouble Code
EVSE	Electric Vehicle Supply Equipment
ECM	Engine Control Module
ESS	Energy Storage System
GM	General Motors
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
HSC	Hybrid Supervisory Controller
HV	High Voltage
HVAC	High Voltage Air Conditioning
HVIL	High Voltage Interlocking Loop
ICE	Internal Combustion Engine
LC HEV	Low Current Hybrid Electric Vehicle



MGU Motor Generator Unit

MSD Manual Service Disconnect

PCB Printed Circuit Board

PDO Process Data Object

PWM Pulse Width Modulated

RPDO Receive Process Data Object

RPM Revolutions per Minute

SOC State of Charge

TCM Transmission Control Module

TPDO Transmit Process Data Object

V Voltage

WTW Well-to-Wheel

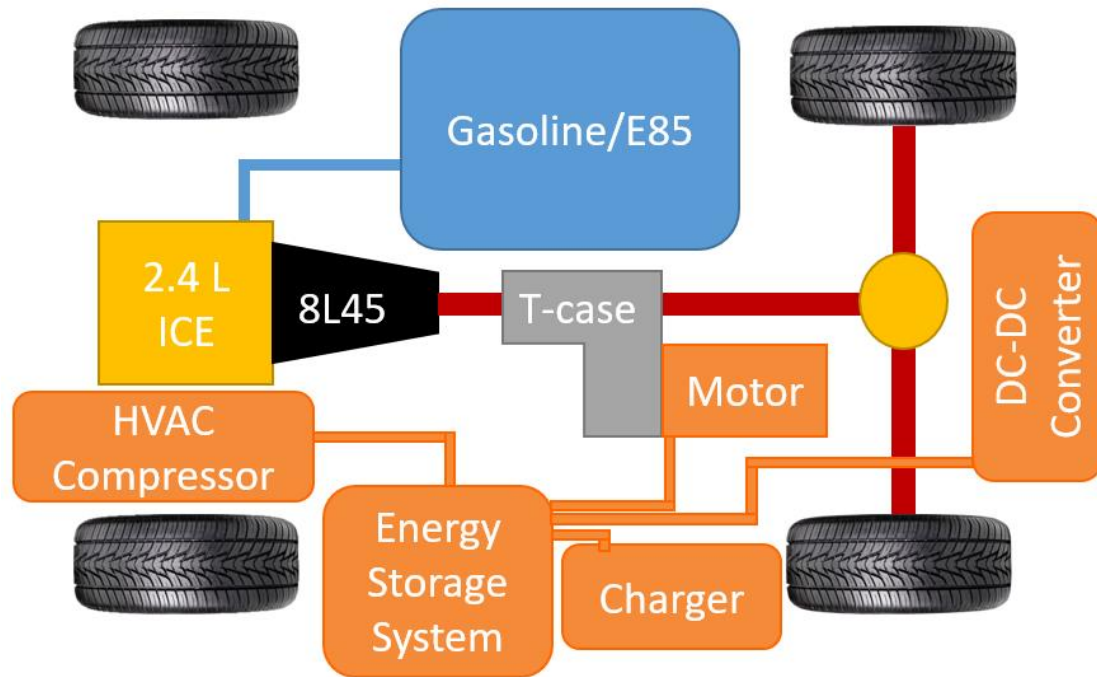
## **SUMMARY**

The purpose of this thesis is to illustrate the deeper understanding and capabilities I have gained as a student at the Georgia Institute of Technology. This will also serve as a useful building block for researchers and student teams involved in hybrid electric vehicle development at this and other universities, and as an accurate interconnect definition document for the Georgia Tech EcoCAR 3 competition vehicle. The necessary steps for the control of various hybrid components in the vehicle will be explained in detail. Specific components to be discussed include, but are not limited to: the hybrid supervisory controller, the energy storage system, the motor and motor controller, the high voltage charger, the electric vehicle supply equipment (EVSE), DC-DC converter, high voltage air conditioning (HVAC) compressor, various pumps, driver notification, and the engine and transmission.

This information was gathered as a result of the EcoCAR 3 competition, established by Argonne National Laboratory (ANL) in partnership with the U.S. Department of Energy and GM to develop new innovations and technology in the automotive industry and to educate students to become future engineers, project managers, and communicators. Each selected university was tasked to modify a 2016 Chevrolet Camaro to reduce energy consumption and well-to-wheels greenhouse gas (WTW GHG) emissions while maintaining consumer acceptability [1].

## CHAPTER 1. INTRODUCTION

In order to discuss the interactions among the various vehicle components, the vehicle's architecture must first be explained. In Figure 1, we see the major components and their interconnectivity. The parts bounded by an orange box are high voltage components, the large blue box denotes the fuel tank, the yellow box is the internal combustion engine, the black trapezoid denotes the transmission, and the L-shaped gray polygon is a transfer case that has been modified for this hybrid application.



**Figure 1: Vehicle Architecture Diagram**

In the current EcoCAR development cycle the Year 1 of competition is devoted to vehicle modeling, architecture selection, and component selection. In Year 2 teams receive the competition vehicle, take baseline data and begin its transition into a hybrid electric

vehicle. The Year 1 and 2 engineering manager for the GT EcoCAR 3 team, Douglas Cox, wrote his thesis, *Model-Based Design and specification of a Hybrid Electric Chevrolet Camaro for the EcoCAR 3 Competition*, describing the development during those first two years. This thesis aspires to serve as an electrically focused second chapter to Douglas Cox's writings.

## CHAPTER 2. HYBRID SUPERVISORY CONTROLLER

The core backbone that holds this 2016 Camaro's components together from an electrical and controls perspective is the hybrid supervisory controller (HSC) and associated peripherals. In the graphic shown in Figure 2, the middle node labeled "Rapid Prototyping-System" is the primary controller that contains all the algorithms and data necessary to make controls decisions. The attached hardware is necessary for interfacing with the various components that will be discussed in the following chapters.

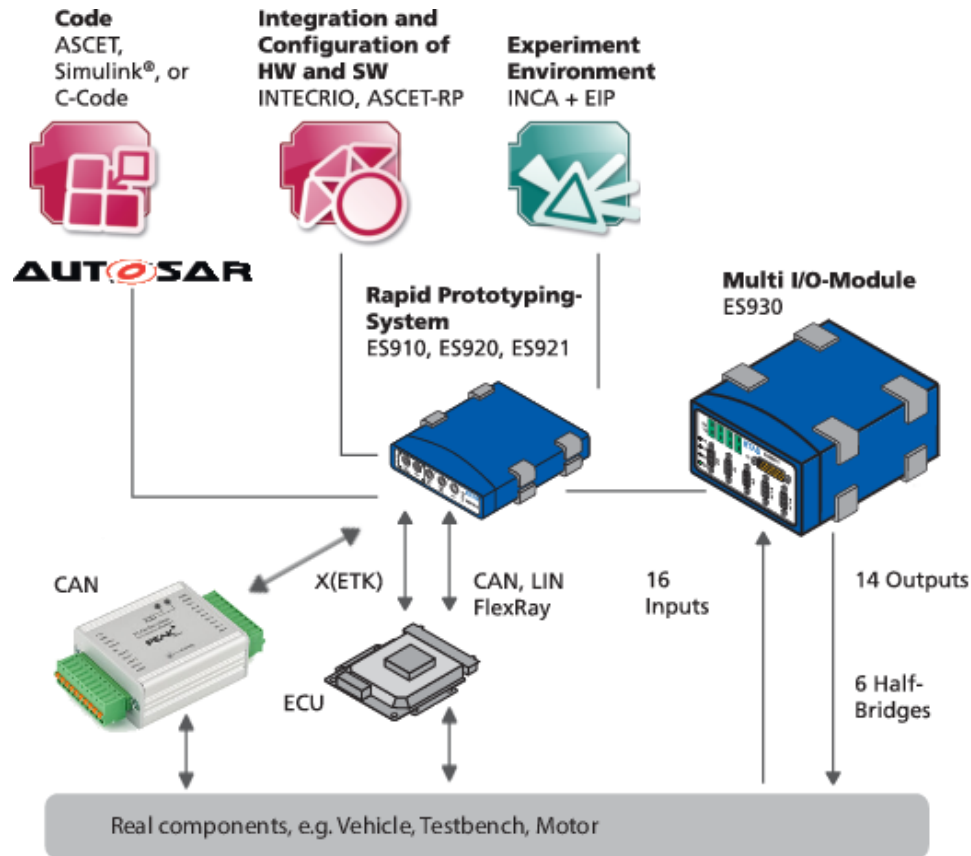


Figure 2: Hybrid Supervisory Controller Architecture [2]

The specific rapid prototyping system used by the Georgia Tech team is the ETAS ES910. The ES910 with the additional controller area network (CAN) bus module supports four CAN busses for communication with vehicle components, Ethernet for programming, and a direct connection to the ES930. The ES910 is programmed with software written in Simulink. This software is compiled using the help of ETAS INTECRIO and then flashed or installed onto the unit using ETAS INCA.

The Multi I/O-Module or ES930 is an analog, digital, and driver module. As an example, this module can take analog inputs from various components such as the potentiometers in the accelerator pedal, process that information and send it as a digital signal to the ES 910. Then, the ES910 will utilize control algorithms to determine what analog signals will be output to the engine via the ES930's analog outputs.

The green and silver module in the bottom left-hand corner of Figure 2 is a PCAN-MicroMod Analog. This device converts analog signals to CAN messages, and CAN messages to analog signals. Two of these devices are installed in the vehicle to supplement the analog inputs and outputs available on the ES930. These modules were selected over an additional ES930 due to cost and size.

When the HSC is being discussed in this document if the signal is sent over CAN, it comes directly from the ES910, but if the data is an analog or digital signal, it would be generated by the ES910 and then transmitted through either the ES930 or a PCAN-MicroMod Analog.

## CHAPTER 3. ENGINE AND TRANSMISSION

During the Year 1 architecture selection portion of the competition, the team elected to use a 2.4 liter naturally aspirated engine designed by GM designated as the LEA. This engine was coupled to the 8L45, an eight-speed automatic transmission that is found on 2016 Camaros. These paired components were chosen for many reasons including support by GM, ease of installation, lower cost and simplified mechanical packaging. The most obvious interconnect is the mechanical connections shared between the engine and transmission. The 8L45 transmission and LEA engine come from different generations and do not have matching bolt patterns for either the bell housing or the flex plate. Figure 3 displays the plate that the team designed to transfer torque between the engine and transmission. This plate and bell housing adapter were machined out of 7050 aluminum.



**Figure 3: Transmission Flexplate Adapter**

The more abstract elements coupling the engine, transmission, and vehicle are the electrical connections and data communication. The team successfully got the engine to crank and run simply by making the appropriate electrical interconnections between the vehicle wiring and engine. However, the transmission was not nearly as simple. The transmission was stuck in fourth gear for nearly a year, which is this transmission's default or limp mode. This issue was ultimately resolved through a process of reverse engineering and with the support of GM. Many different status and command messages had to be implemented on the team vehicle controller. The engine communicates with other components in the vehicle, such as the transmission control module (TCM). Without correct communication, the TCM would output a U100 diagnostic trouble code (DTC), which meant the vehicle could not change gears. These two components are mentioned as a pair because much of their interaction relies on confidential GM information provided as part of a non-disclosure agreement.

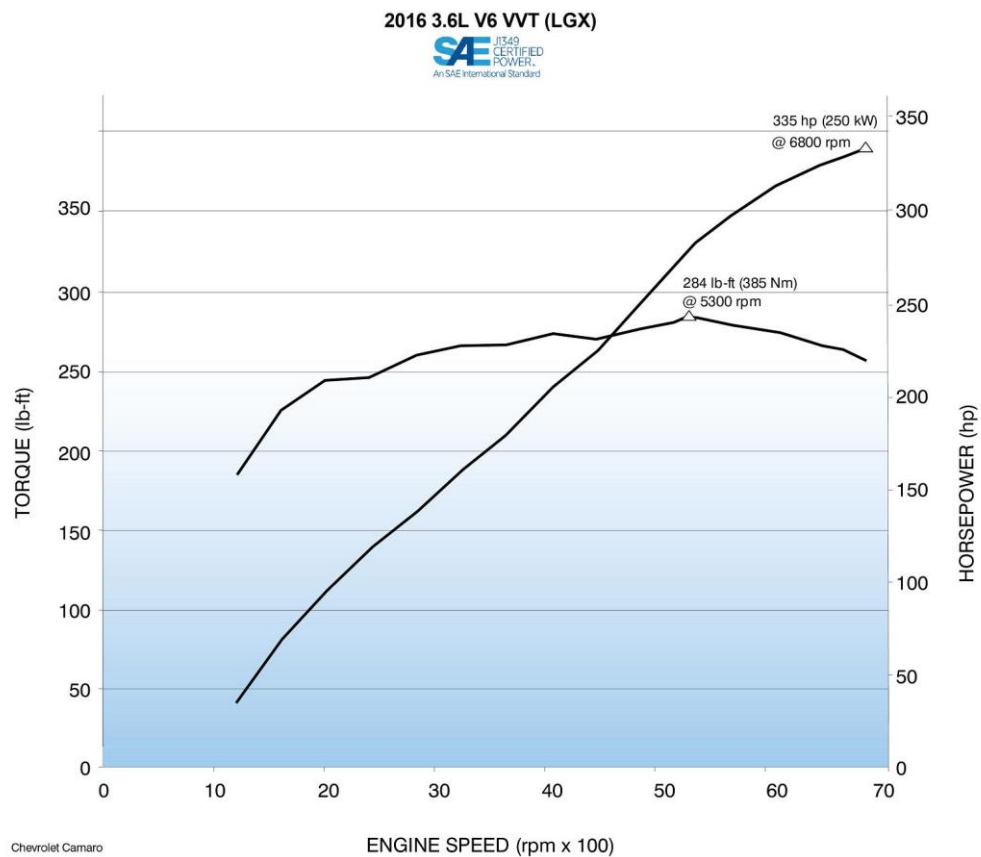
This hybrid electric vehicle reuses the factory accelerator pedal, the team needed more control over what throttle position the engine receives. Rather than simply connecting the accelerator pedal signal directly to the engine, the team modified the wiring to intercept those signals. The engine throttle request and accelerator pedal signals are actually routed to the team controller and the engine receives a simulated output from that controller. Thus, the team can blend the torque desired from the motor and engine together.

As of the fall semester of Year 4 of the competition, the team is using stock transmission mapping. For competition purposes, GM developed a custom flash or software for our transmission so we could command shifts for the transmission with a team-implemented hybrid supervisory controller. However, at this point, other controls related issues took



higher priority. As a result, the Camaro shifts as if the 3.6 L LGX engine was attached. As can be inferred by Figure 4 and Figure 5, these engines have roughly the same shape of curve, but with the LGX generating more power and torque at every point [3] [4].

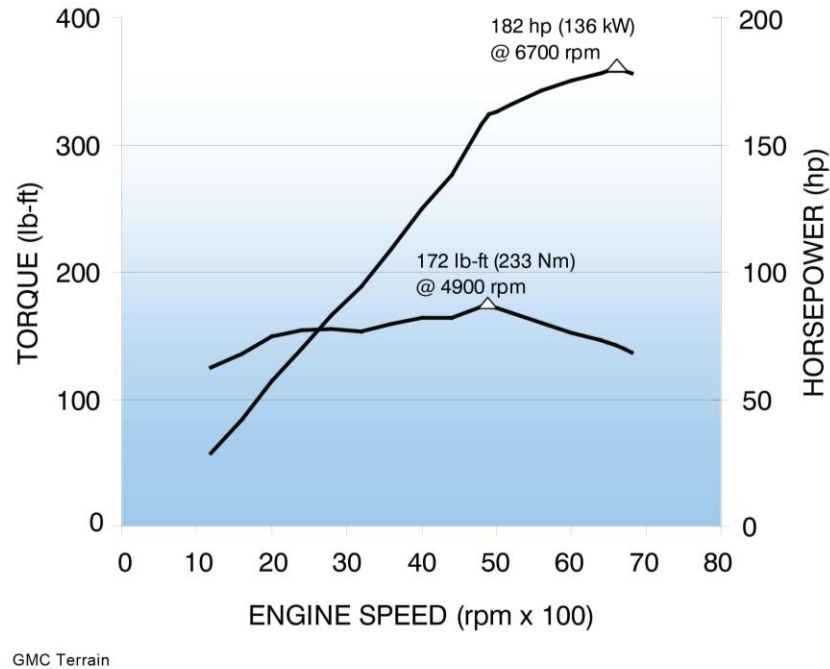
The data displayed in Figure 4 is a dynamometer test evaluation of the LGX calibrated for a Camaro. However, the LEA dynamometer test data is from a LEA calibrated for a GMC Terrain whereas the LEA calibration used in the vehicle is from an Equinox. This should have no impact on the analysis, but is noted to explain the source of the data.



**Figure 4: Stock Engine Torque and Power Graph [3]**

### 2014 Ecotec 2.4L I-4 DI VVT (LEA)

**SAE J1349**  
Certified Power



**Figure 5: Team Installed Torque and Power Graph [4]**

The LGX's maximum safe operating revolutions per minute (rpm) cannot be found in the public domain, but the LFX, which was the precursor and shares significant technology with the LGX, has a maximum speed of 7,200 rpm [5]. This is slightly greater than the LEA's maximum rated speed of only 7,000 rpm [6]. This change can influence when the vehicle upshifts during wide open throttle events.

As discussed in Chapter 5, the competition required an emergency disconnect system, which removes the power to the engine control module (ECM) and fuel pump when one of the emergency stop buttons were pressed, or if the vehicle inertia switch is activated.

## CHAPTER 4. JUNCTION BOX

A central fixture in the hybrid electric Camaro is the junction box which fuses, connects, and shields interconnects. The high voltage schematic for the vehicle is shown in Appendix A. From simply looking at the schematic, it is clear that the junction box is a critical element for the high voltage system. The upper and lower bars on that schematic are reflected as physically higher and lower bus bars within the junction box. The connections from the junction box are fused exclusively on the positive side, with the exception of the motor generator unit (MGU) and the test connector. The test connector is fused on both sides due to its experimental and fault inserting uses. The MGU is not fused because after analysis was performed, the correct fusing for the motor was found to be 250 amperes (A), which is exactly that of the integrated battery fuse. Upon discussion with ANL engineers, the team elected to simply utilize the fuse integrated into the manual service disconnect (MSD) rather than add the possibility of identically fused circuits blowing simultaneously. Were two fuses to blow simultaneously it would make repairs more costly and complicated. As shown in Figure 6, midget/ 5 AG size fuses are used.



**Figure 6: Junction Box**

The variety of current ratings, voltage ratings, maximum fault current, form factor, and availability were the factors used in the selection of these fuses and holders [7]. Littelfuse brand KLK fuses are used for the DC-DC converter, charger, and test connector. Littelfuse also offers low current hybrid electric fuses (LC HEV) in the same form factor. A LC HEV fuse is used for the air conditioning compressor because the datasheet for the KLK fuses states that they are not for applications with high inrush currents [8]. Because the air conditioning compressor has a three-phase brushless direct current motor, relatively high

inrush currents can occur on startup. While the HEV fuses could have been used in all fusing scenarios, the KKK fuses were far easier to source and could be found for smaller rated currents. This was of particular importance for the test connector. The available HEV fuses range from 10 A to 40 A as these currents are reasonable for the various accessory components typically found within a hybrid or electric vehicle [9]. However, as the EcoCAR is a prototype, it needs a test connector that can be used to observe the bus and insert faults such as a ground fault. While the wiring and connectors are sufficient for upwards of 20 A and thus could use a 10 A fuse, the test conductor should never see currents larger than those caused by the impedance of a voltmeter or oscilloscope probe. Additionally, when attempting to source many of the HEV fuses, most sources required a minimum order of 240 fuses, which was far in excess of our needs, whereas the individual KKK fuses were easily sourced from an electrical supply house, Galco.

## CHAPTER 5. EMERGENCY DISCONNECT SYSTEM

The Emergency Disconnect System (EDS) is a purely electromechanical system that runs throughout the vehicle to disable potentially dangerous components or systems if an unintended operation occurs. In Figure 7, there is an emergency stop switch on the rear of the vehicle that is intended to disable the vehicle powertrain, the high voltage (HV) system, and prevent any additional fuel from being pumped out of the fuel tank.



### Figure 7: E-Stop at Rear of Vehicle

Figure 8 shows the emergency stop switch within reach of the driver and passenger. Beside the emergency stop switch is a placard indicating the vehicle's safety status. In this picture, the vehicle status is green indicating it is safe to conduct on-road testing.



**Figure 8: E-stop Within Reach of Driver**

Additionally, there is an inertial switch firmly mounted to the chassis of the vehicle beside the rear right seat. The inertial switch looks like the one shown in Figure 9. Inertial switches typically contain a small loose weight that is trapped within a spring-loaded cage that will spring the mass from its cage when vibrationally shocked to activate the switch.





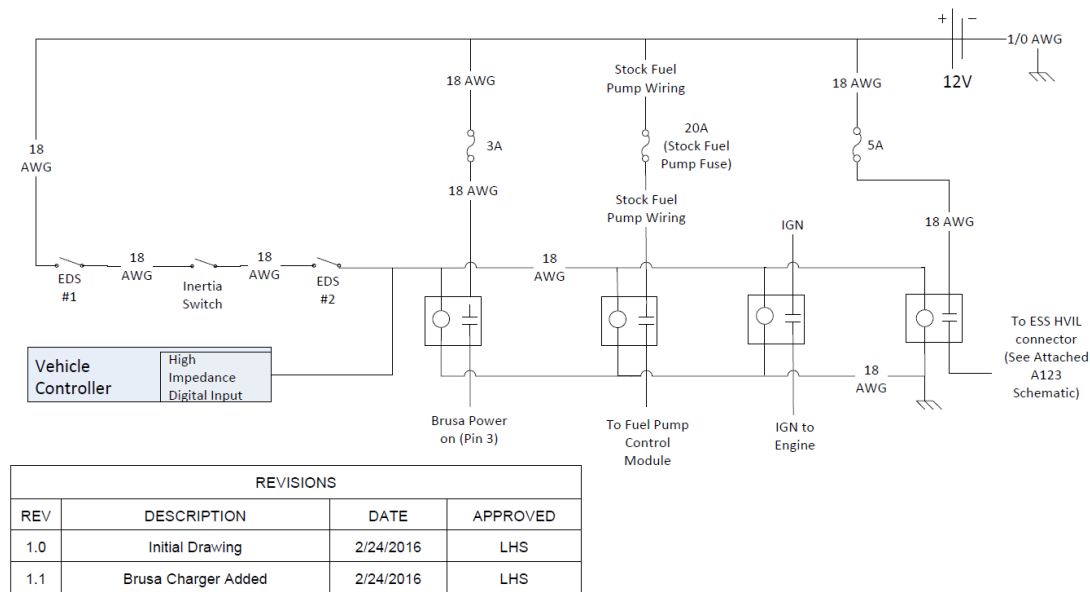
**Figure 9: Inertial Switch before Mounting [10]**

To reactivate the switch, it must be reset by depressing the red button to re-trap the weight. These devices work similarly in conventional vehicles to disable the electric fuel pump in the event of a crash. When the inertial switch was installed in the vehicle during Year 2 of



development, the switch was placed in an awkward location for testing. In order to trip the switch, either a significant crash must occur, or the rear seats must be folded down and the trim panel closest to the driver must be pulled back to a location where the inertial switch can be struck by a tool.

These components work together as part of the EDS to disable the engine ignition, the low-pressure fuel pump, the charger, and the high voltage interlocking loop (HVIL), which disables the ESS. A schematic depicting the specific connections is shown in Figure 10. In this schematic, there is a fused 12V line that has three switches that are normally closed, which supply voltage to the coils of four relays that are normally open. This configuration is a failsafe design such that if any portion of the loop breaks, it will disconnect that component or all components.



**Figure 10: Emergency Disconnect System Schematic**

It may be unusual that the charger is disconnected in addition to the ESS, but it became obvious why this was necessary during the pre-competition inspection. With the Year 3 competition Brusa charger control setup, the charger would continue to supply voltage to the HV bus even after the ESS contactors had opened. This could have been resolved in software by monitoring the ESS HVIL signal and then turning the charger off, but the organizers preferred a hardware method. It may be possible to remove this relay once fully automated communication between the high voltage battery pack and charger is resolved.

HVIL is a safety mechanism that is used in many hybrid electric vehicles. In HVIL, there is a wire that runs through all the high voltage component connectors and housings such that the system will be deactivated whenever a connector is unplugged. Aside from the Energy Storage System (ESS), the components donated for this vehicle do not support HVIL, so the HVIL “loop” goes directly from a fused 12V output through a disconnect relay and to the ESS connector. The MSD on the ESS also uses HVIL.

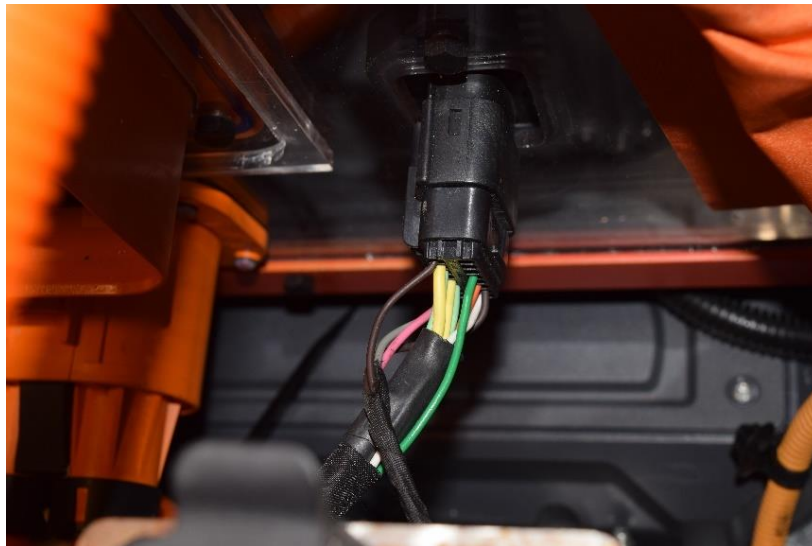
The vehicle controller high impedance digital input has not yet been implemented. The status of this loop is monitored by reading the battery’s perspective over CAN, but this is not wholly representative because it would appear as a different problem if the HVIL fuse is blown or there is simply a wiring issue with the HVIL.

## CHAPTER 6. ENERGY STORAGE SYSTEM

As a part of the documents provided with the A123 battery pack, the Georgia Tech team received a large interface control document titled “EcoCAR A123 ICD.” This is the foundation for the electrical and programmatic connections that need to be made to operate the battery pack effectively. This document contains specific detailed information necessary for the electrical and controls integration into the battery pack. The pinout in Table 1 is colored to match the wire colors used in the vehicle. The low voltage battery pack connector is shown in Figure 11.

**Table 1: Energy Storage System Low Voltage Connector**

1	2	3	4	5	6	7	8
BCM_PWR	BCM_GND	VEH_CANH	VEH_CANL	CAN_GND	MOD_CANH	MOD_CANL	HVIL
CHAS_GND	VEH_WAKE	CHRG_A_WAKE	CHRG_B_WAKE	CHRG_A_ENA	CHRG_B_ENA	PILOT	
9	10	11	12	13	14	15	16



**Figure 11: A123 Battery Connector**

The signals and their purpose will be discussed in reference to Table 1. As would be expected from the signal names, the BCM\_PWR wire is the primary 12V supply line to the battery pack. One would expect this to be directly connected to the 12V output rail from the battery, but for the controls team to have more flexibility this wire is connected to 12V through a relay and fuse such that the HSC can reset the high voltage battery. While never triggered at competition, this was implemented due to a concern that high voltage battery contactors might open and need to be reclosed while driving. If the condition that caused the contactors to open was rectified, this additional feature would allow for a more robust driving experience.

The BCMGND pin is connected directly to the vehicle chassis along with the CANGND pin and CHAS\_GND pin. This is less than ideal as the BCMGND signal can induce noise in the CHAS\_GND and CANGND wires. However, no issues have been detected related to electromagnetic interference, but it would be a prudent decision to attach the BCMGND to one ground point, and the CHAS\_GND and CANGND to a less frequently used ground point.

The vehicle CAN lines are connected to the team HV CAN bus using J1939-11 compliant twisted pair shielded cable with a drain wire. J1939 is one of many standards set by SAE International, an engineering organization that develops standards for many industries, including automotive. A drain wire is a bare copper wire that makes constant contact with the foil or braided shielding. A drain wire allows the shielding to be grounded or extended without needing to crimp to the end of the foil or braid directly. This style of wire is the best to work with as it allows for easy interconnection and extension of grounds in a mechanically robust fashion and offers a more professional appearance.

The MOD\_CANH and MOD\_CANL wires are necessary for an internal CAN bus that the modules and other battery pack internal components use to communicate with each other. Typically, this bus is unused, but access to this bus is useful for troubleshooting and diagnosis. This bus is typically not connected to anything external to the battery pack, but is terminated in a db9 connector.

As discussed in the EDS chapter, and shown in Figure 10, the HVIL wire connected here is simply run to a fused 12V signal. The VEH\_WAKE 12V signal is used to enable the battery pack for vehicle operation. This wire can be supplied with voltage at the same time as the BCM\_PWR line without causing any faults. This VEH\_WAKE cannot be enabled at the same time as the CHRGA\_WAKE as it will cause a fault. This is so that the vehicle can only be driven or be charged, but not both.

The CHRGA\_WAKE signal is intended to wake the battery pack when it is ready to be charged. The battery can still be used to power components such as the DC-DC converter while charging, but the powertrain is disabled.

In order to charge the vehicle, a J1772 compliant charge plug is inserted to induce the Brusa charger to generate a 12V signal that is sent to the battery pack on the CHRGA\_WAKE line. If the battery is in a safe state to charge, it will respond to the Brusa charger on the CHRGA\_ENA line with 12V and control the charger over CAN.

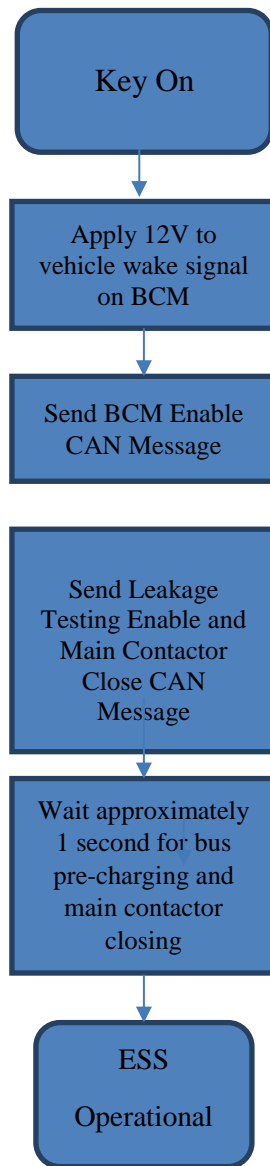
The vehicle status for Year 3 competition had somewhat unexplained internal faults that resulted in malfunctions in the charging mode. As an intermediate solution, the team would simply activate the battery pack using the vehicle wake and force the Brusa charger to charge. When using this less than ideal charging method, the team HSC is required to

control the charging current supplied to the battery as to not exceed the charging limits for the battery. Ultimately, during the summer before Year 4, the correct charging and balancing communication was resolved.

The CHRGB\_WAKE and CHRGB\_ENA lines are not used for the 2016 Camaro as they are intended for use with a 15kW offboard direct current (DC) charger. For the EcoCAR competition, using an offboard charger does not provide any additional benefit as we are restricted to using a J1772 compatible cord set.

A 3.3kW charger allows the 12.6 kWh battery to be charged to full in less than four hours if no balancing is required. If the 15kW offboard DC charger functionality was implemented, the battery could charge in less than one hour, but an additional high amperage DC charging port would be required.

While the specific message IDs and formats are confidential, the general method of control can be discussed. Figure 12 is a battery pack startup diagram that corresponds to what is discussed here. If vehicle operation is desired, the HSC must send a BCM\_Request CAN message to the battery pack. The values or signals in this message are changed to reflect the operation desired from the battery. After the battery pack has received the required power, ground, and vehicle wake signals, it is sent a BCM\_Enable message, which prepares the device for operation. After the battery pack is enabled, it can be sent a main contactor close request that results in the HV bus being energized if the conditions are acceptable for the contactors to close.



**Figure 12: Battery Startup Diagram**

Additionally, the A123 BMS has ground fault detection capability that must be enabled via CAN. In order to enable ground fault detection, the `bcm_leakage_ena` bit must be set to 1 in all subsequent messages sent to the battery. EcoCAR 3 non-year specific rules require that a present ground fault should be detected if it persists for more than one minute,

which is indicated by the vehicle status lights above the rear-view mirror [11]. The team implementation was far more responsive than competition requirements and would illuminate and latch the driver notification lights after a few seconds of detecting a ground fault.

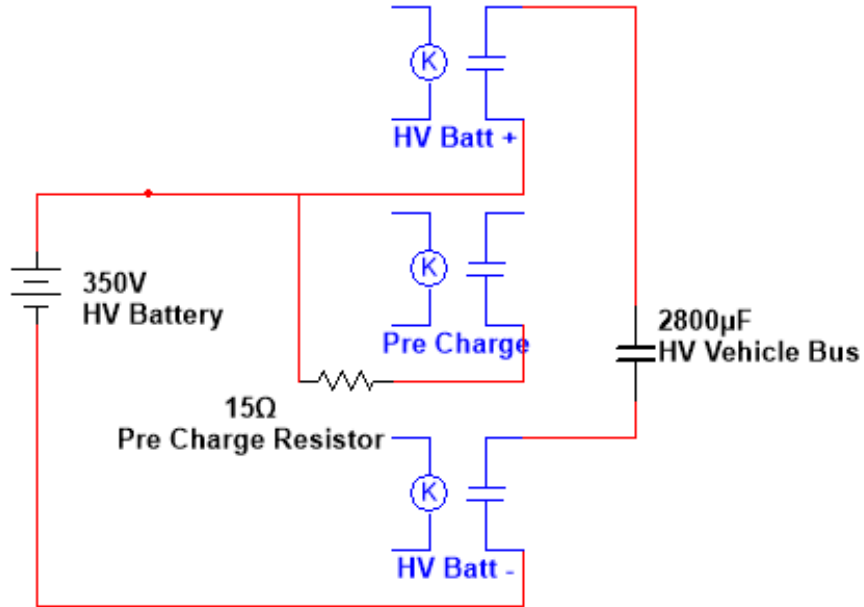
This fault detection relies on a CAN status message from the battery pack and the HSC activating the LED when the `bcm_gfd` message displays less than  $192\text{k}\Omega$  of resistance. This value is determined by the competition requirement as per the non-year specific rules of  $500\Omega$  of isolation per battery pack volt. The maximum listed pack voltage for this battery is  $384\text{V}$ ; thus, when multiplied,  $192\text{k}\Omega$  of isolation is required. Upon seeing a value equal to or less than that, a digital output from the HSC enables the corresponding LED and latches it on until the vehicle is shut down.

The A123 battery pack, like most automotive grade battery packs, uses a three-contactor system. A schematic of these connections is shown in Figure 13.

There is a contactor for the negative, positive, and positive through resistor bus rails. In an ideal case only one main contactor is needed to connect and disconnect the battery from the bus, but the use of two main contactors allows for greater isolation and safety. When the positive and negative contactors are used, the battery management system (BMS) can detect if any of the contactors have been welded. When relay contacts open under load the inductance of the system causes a voltage spike across the contacts and energy to be dissipated into the contacts heating them to a point where they might be unable to separate when expected. In battery packs such as this one, one of the biggest safety concerns is that



the battery contactors would be unable to open and could electrocute service or rescue personnel when service is attempted.



**Figure 13: Battery Contactor Schematic**

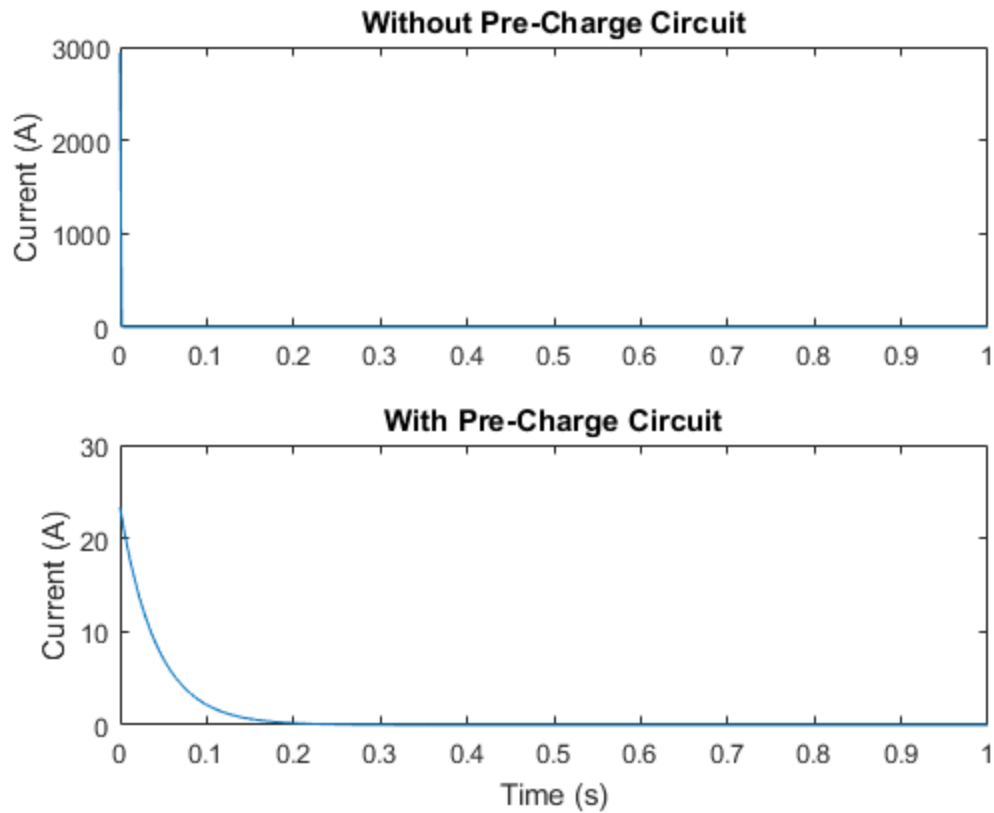
The additional contactor is used as a pre-charge contactor, which connects the positive battery bus to the positive vehicle bus through a resistor. This use of a resistor results in a much lower inrush current. This lower inrush current reduces electromagnetic interference from a high current impulse, reduces wear on components from high current surges, and eliminates the possibility of blowing a fuse as a result of a power surge.

In order to discuss this battery pack in greater detail, analysis was carried out based on publicly available data to determine the internal resistance and ultimately the current produced during contactor closing. This A123 battery pack is composed of seven modules in series and within those modules 15 cells are in series and two cells are in parallel. This

configuration is referred to as 7x15S2P. As the module connections are purely series, this configuration is effectively a 105S2P configuration. The cells used for this battery are 20Ah prismatic pouch cells combined into modules. The datasheet for these cells states that each cell has 2.3 m $\Omega$  of resistance, so the combined pack resistance is 119 m $\Omega$  [12].

Using a Philips PM6303 RCL meter, the DC + to DC- vehicle bus capacitance was found to be 2.8mF, as measured from the HV junction box. This measurement is validated to a degree by the datasheet value of 1.88mF of capacitance from the Sevcon motor controller alone [13]. The motor inverter is by far the highest current device on the bus and so should carry the most capacitance. The other factors in this capacitance include mutual capacitance of the bus bars, wiring within the vehicle, HVAC compressor, DC-DC converter, and the charger. As a side note, when testing the capacitance of the bus, the Brusa charger can be removed with no measurable change in bus capacitance. The A123 battery specifies that the vehicle bus capacitance must be less than 15mF to safely be used with the supplied pre-charge resistor. Clearly, the vehicle HV bus meets this requirement based on this testing.

As Figure 14 depicts, the current required to charge the capacitors based on calculated battery pack internal resistance when the contactors close would be 2941 A—far in excess of the ratings of contactors and fuses. With the 15 $\Omega$  pre-charge resistor circuit in place, the maximum current at the point of contactor closing is 23.3 A. This smaller current is well below any of the system's components ratings.



**Figure 14: Pre-charge Circuit Analysis**

The battery voltage and currents are monitored throughout the pre-charging process, as this pre-charge contactor setup is intended to increase the bus voltage at a safe rate and is not intended to be used to supply devices. The BMS will sense if vehicle components are drawing current during the pre-charging process. If components are on and drawing current during the pre-charge delay, the resulting fault will be sent over CAN. This will prevent the contactors from closing correctly. The team discovered this issue because the DC-DC converter was initially hardwired to turn on as soon as it received HV power, but this prevented the contactors from closing. As a result, the team disabled the DC-DC converter until the battery contactors were closed.

## CHAPTER 7. MOTOR AND INVERTER

The motor and inverter combination is operational, but the team faced significant difficulty when trying to wire and program the inverter. As a result, it took months to properly communicate with the inverter in order to generate torque from the motor. These issues came primarily as a result of initially insufficient documentation on the Sevcon inverter, but were ultimately resolved via some documentation and feedback from the reseller, NewEagle. Based on interacting with competing universities who use similar hardware from different manufacturers, it was clear that the Sevcon was an excellent choice for our application due to its robustness.

Ultimately, we determined that the connections shown in Figure 15 were the only low voltage connections necessary to provide tractive control, but that other connections can be added for increased functionality. The necessary low voltage connections include power, CAN, one heartbeat loop, resolver feedback and one or more thermistors. These are in addition to the two wires for HV DC from the battery and three wires for HV AC to the motor.

The Sevcon inverter allows messages transmitted to and from the inverter to be programmed via the DVT software [13]. This inverter is programmed over CAN using an IXXAT USB-CAN device. The use of this system has its benefits and drawbacks. Conveniently, no additional communications connections are necessary, but when the motor is being reprogrammed over CAN, it is often necessary to move the inverter to a less congested bus to prevent programming faults. As a result, during significant motor testing,

a separate bus is created that will host only the inverter, IXXAT programming tool, and a Vector CANCaseXL.



**Figure 15: Motor Generator Unit Connections**

This inverter uses CANopen as its communication protocol. CANopen is a layer that runs on top of the typical CAN data link and physical layers. Figure 16 is the primary receive process data object (RPDO) expected by the Sevcon: it is the only message that the Sevcon inverter must receive in order to operate. As with any device using the CANopen protocol, these process data objects (PDOs), whether receiving or transmitting, can only be transmitted in the “Operational” state [14]. Additionally, error messages from the Sevcon are sent over CAN, but are not documented in the Sevcon manual. As a result, if a fault situation occurs, a CAN message is sent, but is only intelligible if the DVT tool is open and the IXXAT tool is connected. To improve the robustness of the vehicle, CAN logs could be reviewed and correlated to fault events so that the team would have a database of faults that occurred before and can recognize those faults so the team controller can adapt accordingly.

### RPDO 1 (dcf)

Cob-ID for this PDO: 0x000007A1

Syncs Per Transmit: 1

Bits: 16 | Adr: 0x6071,ROOT | Target torque  
Bits: 16 | Adr: 0x6040,ROOT | controlword  
Bits: 32 | Adr: 0x6080,ROOT | Maximum motor speed

Bits Used:
64

Bits Left:
0

Remove Item
Add Item

Move Item Up
Move Item Down

Read PDO
Write PDO

Add dummy boolean
Add dummy 8bit
Add dummy 16bit
Add dummy 32bit

**Figure 16: RPDO Programming Interface**

This receive process data object takes in critical information and must be 64 bits to be sent. If it is less than 64 bits, either additional signals or dummy bits can be added to send the message for transmission. The transmit process data objects, such as those displayed in Figure 17, is the method of getting data out of the motor generator unit to make controls decisions.

TPDO 5 (dcf)	
Cob-ID for this PDO:	0x00000167
Syncs Per Transmit:	1
Bits: 32   Adr: 0x606C,ROOT   Velocity Bits: 16   Adr: 0x6040,ROOT   controlword Bits: 16   Adr: 0x4600,12   Actual AC Motor Current	
Bits Used:	64
Bits Left:	0
<a href="#">Remove Item</a>	<a href="#">Add Item</a>
<a href="#">Move Item Up</a>	<a href="#">Move Item Down</a>
<a href="#">Read PDO</a>	<a href="#">Write PDO</a>

**Figure 17: TPDO Programming Interface**

These messages are fully configurable as the CAN ID and the order of the signals received by the Sevcon is user programmable. As long as the controller for the motor has a .DBC file that matches these messages, it can communicate correctly. A .DBC file is an industry standard file format for storing CAN message formats, units, and descriptions. The team has had some difficulty in the past with matching the units used by the Sevcon controller with physical units, but that was resolved with data testing and some back calculation.

In this vehicle, the motor is controlled via a torque control mode as opposed to a speed control mode. Torque control allows for more refined and safer motor control. In the torque control mode, the vehicle can request zero torque when fault conditions occur, but in a speed control mode, the controller either must request a specific speed or be disabled, which presents some issues for smooth operation.

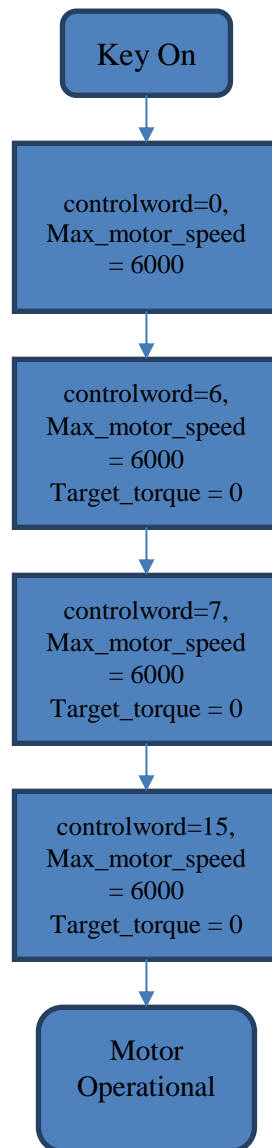
In this configuration, the target torque is the quantity of torque desired from the motor. The “controlword” is a value that determines the status of the motor controller to some degree. Through the “controlword” value and the sequence with which it is updated, the motor controller can be activated and deactivated. The maximum motor speed value is the maximum value at which the motor will be allowed to operate.

For this system, there are many different types of limits, but specifically for speed, there are the mechanical limits of what the motor can handle, what the chain within the transfer case can handle, what the motor generator unit can supply, and what is safe for the vehicle driveline. In our application, we discovered that the chain drive the team used to connect the electric motor to the powertrain was the limiting factor. This chain supports a maximum speed of 6,000 rpm. The motor itself can handle 10,500 rpm, and the motor generator unit can easily be sped to 6,000 rpm before hitting any voltage limitations with the attached A123 battery. The other driveline components have been validated in excess of 150 mph by GM. Based on the sprocket ratios used during Year 3 of competition, a 6,000 rpm motor speed results in a vehicle speed of 91 mph. While this is in excess of any United States legal speed limits or competition requirements, it is still somewhat limited for a muscle car.

To prevent any mechanical issues, the team set two types of limits that ultimately resulted in a fault that was difficult to decipher. As discussed previously, a maximum speed value is continuously sent via CAN, which is handled gracefully, but an encoder fault occurs when the hard limit programmed within the firmware is set to the same value as the maximum speed limit sent over CAN and that speed is reached. Our team encountered a complication as it set the hard limit and soft limit to the same value. This can be remedied by setting the speed limit via CAN to a speed slightly lower than what is hardcoded. As an



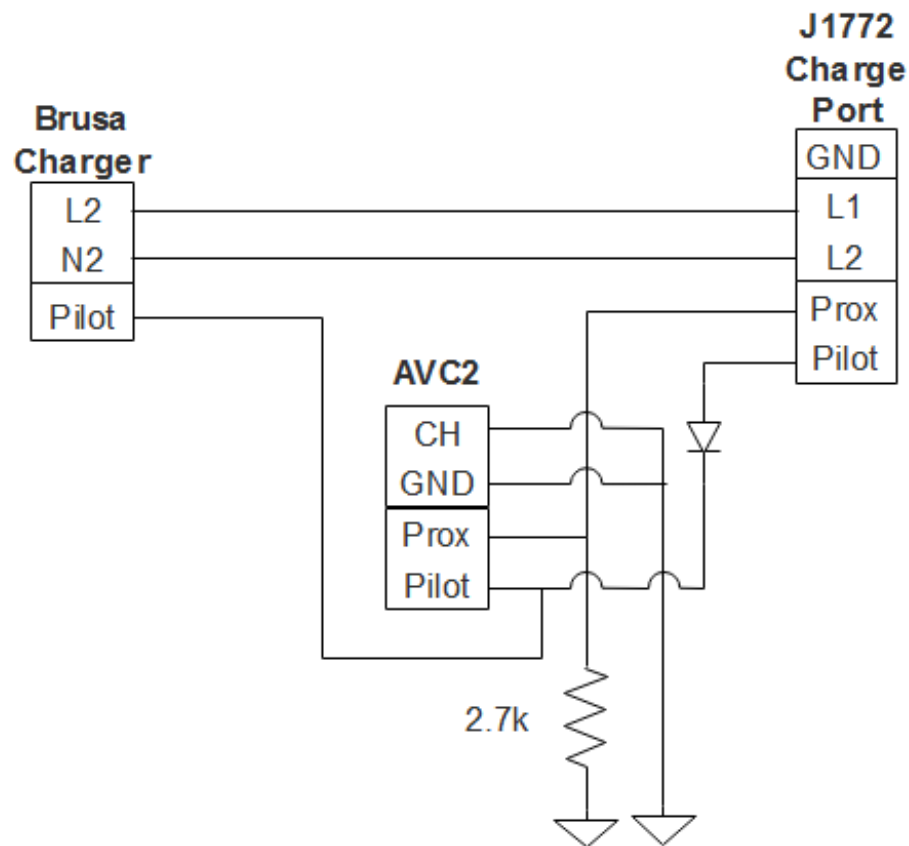
example, the team is now sending a 6,000 rpm max speed limit and hardcoding 6,100 rpm as a maximum speed limit via CAN. The startup sequence required for motor operation is shown in Figure 18. Once the motor has completed the startup procedure, the team HSC can use the target torque command to change the amount of propulsion desired from the electric motor.



**Figure 18: Motor Startup Procedure**

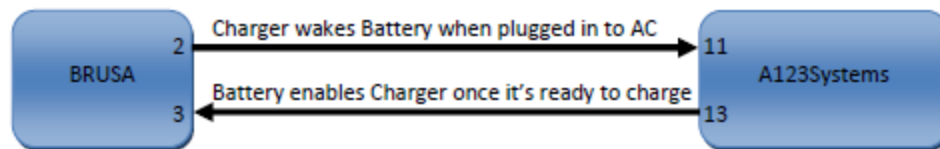
## CHAPTER 8. CHARGER, EVSE AND CHARGE PLUG

The charger high voltage AC and DC connections were implemented according to the manufacturer's recommendations and datasheets. The charger is one of the more complex components in terms of the quantity of different devices that interface with this device. A schematic depicting the different connections is shown in Figure 19. The connections permit any J1772 compliant charging station to charge the vehicle.



**Figure 19: Camaro Charger Interface**

In the A123 ICD, there is an important diagram outlining the process for enabling the charger and managing charging as shown in Figure 20. The specific A123 battery packs donated by ANL have been programmed to interface with the Brusa chargers that are used by all of the plug-in hybrid electric vehicles in the competition. The Brusa charger is capable of 3.3kW power input for level II charging and 1.4kW of power input for level 1 charging. The Georgia Tech EcoCAR 3 team has Rose Hulman Institute of Technology to thank for the generous donation of the EcoCAR 2 Brusa charger.

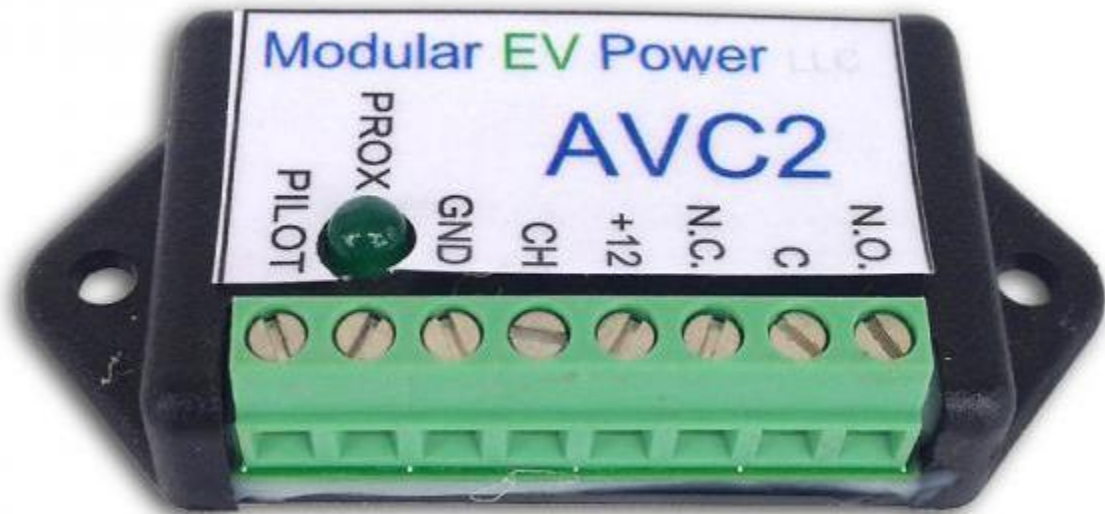


**Figure 20: Charger Enabling Process**

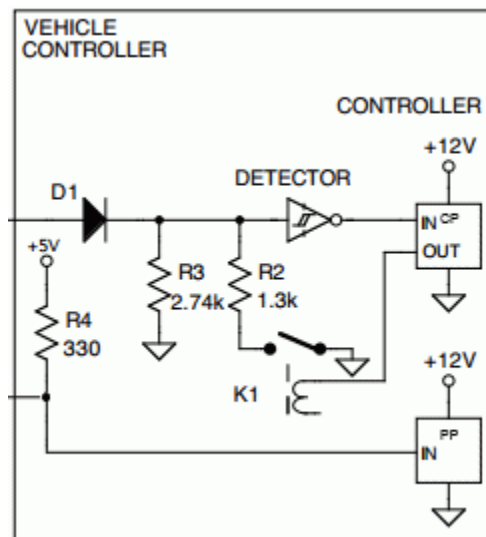
The correct way for the charger and battery pack to interface is for the battery charger and the A123 battery pack to be wired together such that when the J1772 charge plug is inserted into the vehicle, the battery pack and charger will turn on together to communicate and coordinate charging and cell balancing. Unfortunately, in Year 3 of the competition, four distinct difficulties were faced when interfacing with the battery, charger, and electric vehicle supply equipment (EVSE). These included being unable to charge in any fashion, being unable to charge at a level II charger, being unable to charge automatically, and balancing the battery cells. The initial problem, being unable to charge in any fashion, was addressed partway through Year 3. As a temporary solution to allow for level I charging, the team was able to charge the battery pack in the “main” operation mode of the battery as if it were ready for driving. This had the unfortunate side effect that the team then needed

to manage the flow of current directly, and were unable to balance the battery cells, but did allow the team to meet the requirement to charge as a part of the Emissions and Energy Consumption event.

In order to prevent the battery pack from overcharging and opening the battery contactors, the charge buffer of the A123 battery pack was closely monitored, and the current into the battery pack was varied. This buffer is a value that ranges from 0 to 100% and is reported over CAN. This buffer represents the instantaneous power that can be input into the battery. When the power input into the battery pack is increased, the buffer correspondingly decreases. In order to charge the battery as quickly as possible, the battery is charged at full current available from the charger until a certain state of charge (SOC) value is achieved; at that point, the current input will decrease to prevent the charge buffer from reaching zero. The second issue, being unable to charge at higher currents from a level II or 240VAC charger, was not discovered until Year 3 competition. Before the competition, an AVC2 device shown in Figure 21 was installed in the vehicle with appropriate wiring. This module is intended to facilitate our charging system's ability to communicate appropriately with the electric vehicle's supply equipment that is J1772 compliant. This module was selected because it allows for simplified control of the Brusa charger. The team had many difficulties with the charging system, including correctly interfacing with the EVSE's pilot signal. Inside the AVC2 module there is likely a circuit that looks similar to the circuit shown in Figure 22.



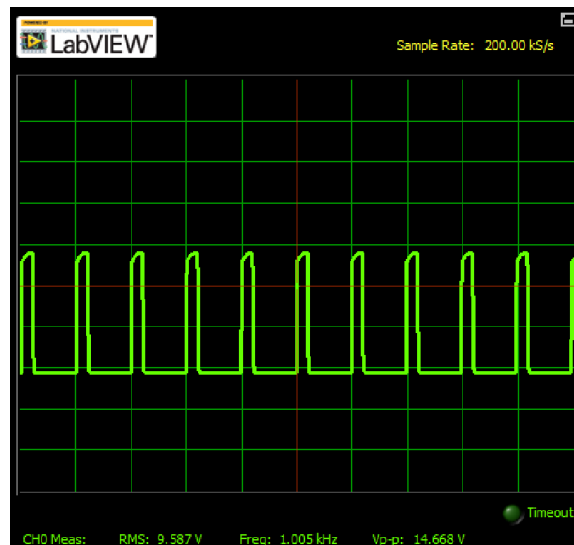
**Figure 21: AVC2 J1772 Controller [15]**



**Figure 22: Vehicle Side J1772 Charger Circuit [16]**

This circuit contains all of the necessary components with the exception of a mandatory 2.7k resistor between proximity and ground. A different module, the AVC2.r, has the

necessary 2.7k resistor already included in the module, but that was only discovered once the AVC2 documentation was received. Unfortunately, this module does not allow for access to the cathode side of the diode labeled as D1. As a result, the square wave in Figure 23 measured from the AVC2 device's pilot line terminal had a negative component whereas the internal cathode will have that negative portion removed. This is significant because the Brusa charger expects to see the output of that pilot signal with a positive square wave. Consequently, when attempting to interface with level II chargers, the Brusa will not try to charge the battery. In order to solve this problem, another diode was added in line with the J1772 pilot signal to remove that negative component before it was intercepted by the Brusa charger or AVC2 module.



**Figure 23: Square Wave produced by EVSE**

The lack of balanced cells began to present an issue before competition and throughout with the emissions and energy consumption event. The battery pack modules are rated at a minimum of 12.6 kWh, but the effective battery capacity was only 7.6 kWh due to the imbalance between the minimum and maximum voltages of differing cells. Of the 210 cells

in the battery pack, no two cells have the exact same chemical or electrical characteristics and when the cells are charged and discharged, an imbalance of cell voltage can occur as a result. In order for the cells to not be degraded, the battery management system (BMS) of the battery pack will prevent additional current entering the battery pack at high cell voltages and will prevent current from leaving at low cell voltages. As a result, the minimum and maximum bounds for which the battery can be charged and discharged change over time. This mismatch also resulted in the SOC value becoming unreliable. State of charge is a 0% to 100% value that represents the available energy in the battery pack; at 100% SOC, the battery is fully charged, and at 0% SOC, there is no energy available. To prevent this issue from impacting the team's ability to complete competition events, the team set more conservative boundaries for where to stop charging and where to stop drawing energy.

This resulted in reliable vehicle operation at the cost of reduced fuel economy and increased emissions because the team was still moving the weight of a 12.6kWh battery around without the additional energy storage capability. When the battery was nearly fully charged, there was approximately a 100mV difference between the cell minimum and maximum voltages. That is a significant energy difference for lithium batteries of this nature.

Programming of the charger and wiring improved during the summer between Year 3 and Year 4, such that the A123 battery pack now has the capability to enable the charger and communicate with it over CAN to coordinate the desired current input and coordinating balance.

## CHAPTER 9. DC-DC CONVERTER

The DC-DC converter the team is using was produced by Denso for the Generation 3 Prius. Our team sought to find connectors that are native to the Prius to avoid additional modification, but the competition organizers did not feel that the original connections were sufficiently finger safe for high voltage, and we found that the low voltage connections were cost prohibitive to procure for a single use.

As a result, the team modified the circuit board that supplies the control signals to accept an industry standard Delphi GT150 connector. This modification was completed by soldering a purple wire to the 12V supply line on the circuit board through the GT150 connector to a fused 12V supply. A white wire was also soldered to this printed circuit board (PCB) to connect a control wire through the gt150 connector to the ETAS 930. This white control wire activates and deactivates the DC-DC converter. This allows the team to use common connectors throughout the vehicle and be more prepared if any connectors are damaged in the vehicle while testing.

The high current low voltage connection was wired with a thermoformable plastic cover to reduce the likelihood of shorting the 12V power output to the vehicle's chassis. Additionally, 1/0 AWG wire was reused from the ESS build process for connecting the DC-DC converter to the large fuse block. While this is larger than necessary—as 1 AWG would have been sufficient—the team already possessed the 1/0 AWG wire and wire lugs for that wire gauge. After crimping the appropriate lugs, this wire is wrapped in a matte black anti-abrasive tape to prevent wire damage and to designate that this is a low voltage



wire. This last step is significant because the wire's insulation is orange and, for the purposes of EcoCAR, any orange wire is expected to possibly conduct high voltage.

To complete the voltage loop, the DC-DC converter is grounded through the mechanical connections on the unit to the chassis of the vehicle. These connections had the paint removed chemically and mechanically to reduce contact resistance. After that, rivnuts were installed in order to hold the DC-DC converter in place. Rivnuts are a valuable tool for inserting threads into sheet metal without welding.

The high voltage connections that Denso uses in the Prius were removed and soldered to a 14 AWG Champlain Cable shielded FX wire. This wire has a greater diameter than the wire affixed to the unit from the manufacturer, but was the closest readily available size that was rated for these voltages and conditions.

The control of this unit is quite straightforward. The unit will turn on if the 12V analog supply is connected to 12V and the control signal is either left floating or connected to greater than 1V. This DC-DC converter is able to maintain a constant 14V output even when the 12V battery is disconnected. While this is a benefit in regular operation, it results in the competition required 12V disconnect having no apparent effect if the DC-DC converter is operating. As a semi-temporary solution, the team cycles the DC-DC converter off for 2 seconds every 20 seconds in order to ensure that the 12V bus powers down when the 12V disconnect is switched. This could be improved in the future by adding a switch inside the 12V disconnect to disable the DC-DC operation when the 12V disconnect is in the off position.

## CHAPTER 10. HIGH VOLTAGE AIR CONDITIONING SYSTEM

As with the DC-DC converter, the HVAC compressor the team is using was produced by Denso for the Gen 3 Prius. Our team sought to find the stock connectors, to avoid unnecessary additional modification, but we abandoned that plan when we discovered that the low voltage connections were cost prohibitive to procure for a single use. Thus, the team replaced the low voltage connection with a GT 150 connector and soldered the HVAC electrical compressor connections into wires that run directly to the rear junction box. This comes at the disadvantage of requiring that all the retaining clips shown in Figure 24 must be removed before the HVAC can be removed if repair or replacement is required.



**Figure 24: HVAC Underbody Wiring**

This device has a straightforward initial control process. After being re-pinned to a GT 150 connector, the AC compressor pinout is shown in Table 2 with corresponding wire colors.

**Table 2: HVAC Low Voltage Connector**

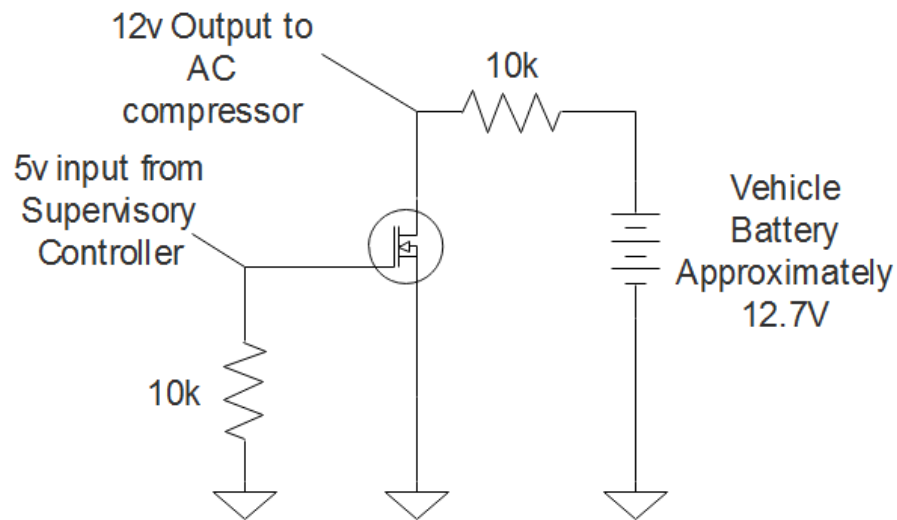
Pin	1	2	3	4	5	6
Color	Black	Grey	Green	Yellow	Pink	Red
Function	Gnd	Diagnostics	PWM out	PWM in	On/Off	+12V

In this application, the 12V supply is fused at the front fuse box at 7.5A and connected with an 18 AWG wire. The amperage supply requirements were not defined in the Denso AC compressor documentation, but this combination would be safely fused in the event of a short to the chassis. This combination has not resulted in any issues, but could be further analyzed in the future. The ground is connected to the chassis near the compressor.

After testing the compressor in multiple startup sequences the team determined that, for simplified control in Year 3, the compressor on/off signal, which is an active low signal, could simply be connected to chassis ground and the compressor could be turned on and off by supplying an appropriate pulse width modulated (PWM) signal. This saved one valuable output signal at the cost of possibly increased quiescent current. This could be investigated further to reduce unnecessary current draw.

The team experienced significant difficulty when first interfacing with this device. After the mechanical, fluid, and electrical connections were made, control was attempted with a function generator. The function generator used was an Agilent 33120A with a peak

to peak voltage of 10V. This AC compressor PWM signal must receive a higher voltage of approximately 12V before acknowledging the signal. In an ideal case, a 12V output would come directly from the HSC, but there were no additional 12V outputs available due to hardware limitations. However, low current 5V outputs were still available. Thus, a simple amplifier circuit such as shown in Figure 25 is necessary for the hybrid supervisory controller to correctly control this device using a 5V high impedance output.



**Figure 25: AC Compressor Level Shifter**

As of Year 3 competition, the AC compressor was simply open loop controlled by sending a 50% duty cycle to the compressor, which results in a desired speed of 4,700 rpm. This was sufficient to reliably cool the driver's headrest to 10°C below the initial temperature per EcoCAR 3 rules.

A pressure sensor was attached to the high side of the AC system when it was installed. This sensor could be used to control the system using a PID controller to maintain a certain high side AC pressure for safety and reliability.

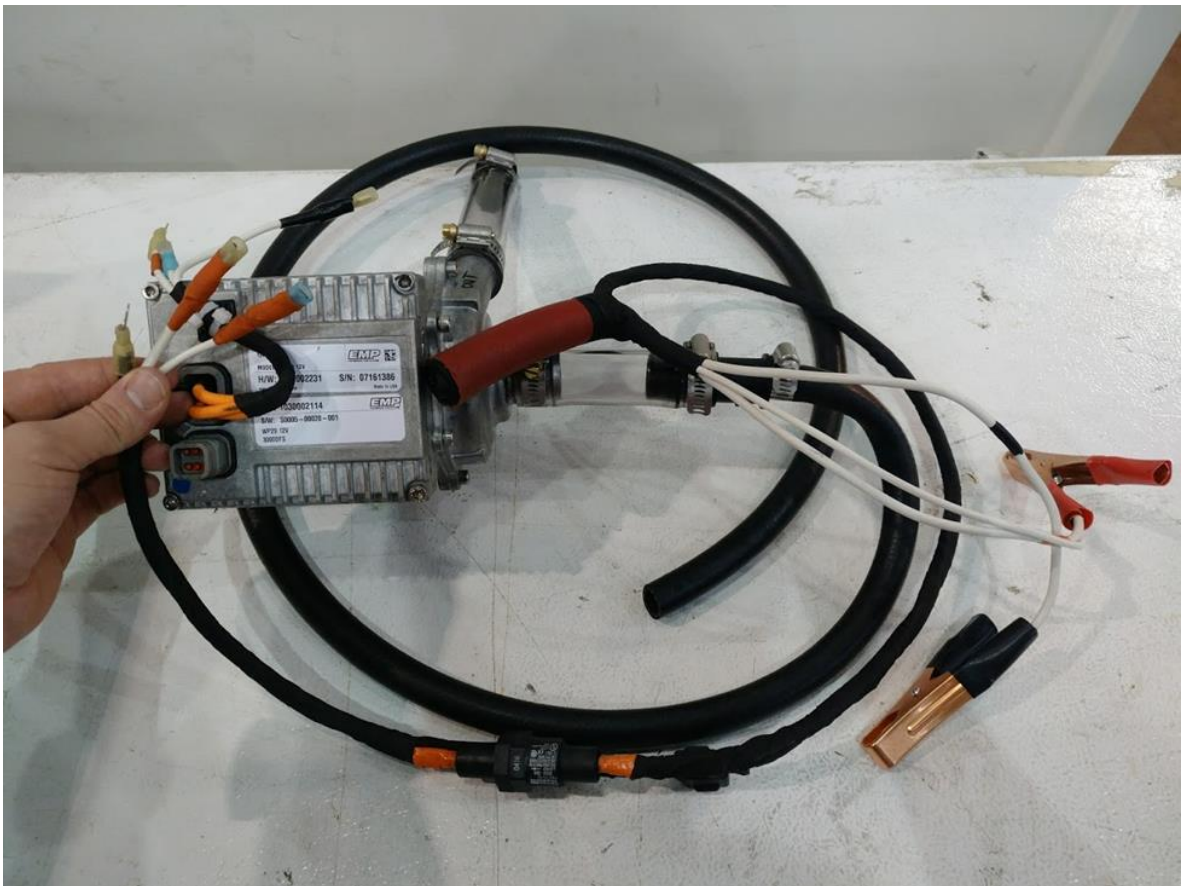
## CHAPTER 11. COOLANT PUMPS

The team selected Johnson Pump SPX mag drive pumps, which have a high flow rate for their size and energy consumption. The other pump the team primarily considered was an Engineered Machine Products WP29 pump, which is more powerful and is controlled via CAN. Unfortunately, the WP29 pumps available for donation at our time of request only support 250 kbps CAN communication. As a result, these pumps would have needed another CAN bus exclusively for pumps, rather than the 500 kbps busses used for all other components. The WP29 pumps have a weight of 6.5 lbs per pump and require significantly more wiring. The SPX pump weighs only 1.3 lbs, but comes with a tradeoff of having no self-priming capability.

Even when installed in the optimal orientation per the documentation, the SPX is susceptible to losing pumping pressure if a small air pocket reaches the pump. As a result, the system needs to be thoroughly purged of air using a more powerful pump. Fluid must be pumped through the SPX pump with the input side of the pump disconnected to flush a large quantity of water through the system until the fluid coming out is clear of most bubbles. There is a clear distinction between the small quantities of bubbles associated with typical imperfect laminar flow and the presence of air in the system. After rapidly reconnecting the part of the system used for purging, a small quantity of fluid can be pumped in through the external pump to pressurize the system. Then, that pump is disconnected and the fluid reservoir is filled to the appropriate level.

Shown in Figure 26 is the EMP W29 pump with a wiring harness and sufficient tubing adapters that allow us to purge the system. Additionally, a Snap-On radiator purge kit is

often used per the supplied instructions. Using these purge tools in combination with driving to slosh the coolant around in the system and bring air pockets to the top is necessary for full cooling efficiency. A more permanent solution would be the addition of two cooling reservoirs that could contain sufficient fluid to displace air bubbles as the vehicle being driven.



**Figure 26: Coolant System Purge Pump**

## CHAPTER 12. NOTIFICATION LIGHTS

The competition requires that each team have notification lights and switches, as shown in Figure 27. The vehicle ready light is intended to indicate when the powertrain is ready to operate. In situations where there is a major fault, such as the interruption of the high voltage interlocking loop, the vehicle ready light would turn off. The ground fault light is illuminated based on the isolation resistance measurement taken from the A123 BMS discussed in Chapter 5. The ESS charging light must start blinking when charging and illuminate solidly once fully charged. The switches displayed are to enable internal combustion only engine (ICE) operation, a charge sustaining mode, and regenerative braking.



**Figure 27: Vehicle Notification Lights**

The switches displayed are to enable internal combustion only engine (ICE) operation, a charge sustaining mode, and regenerative braking. The internal combustion only mode



disables the electrified powertrain, such that the engine generates all power and regenerative braking is disabled. The charge sustaining switch changes the vehicle mode from charge depleting to charge sustaining. The regenerative braking switch enables or disables regenerative braking—note that this mode will be overridden by the ICE only switch. These different modes are required to be tested at the competition to verify their safety.

After this picture was taken, the ICE only mode has been changed in the rules as a mode that turns on engine charging. This is most applicable to teams that have some series hybrid mode whereby they can run the engine to charge the battery pack while stationary. This could have some application in this Camaro as it could enable a mode where the engine operates at a higher power than is necessary for propulsion and the extra power generated could be used to charge the battery.

Due to limitations of the ES930's input and output system, these lights utilize a common ground and are illuminated when the ES930's PS pin supplies a positive voltage. These lights are 12V tolerant light emitting diodes. The switches shown in Figure 27 share a common positive, and the other lead is directed to the ES930 with a pull-down resistor internally set in the ES930.

## CHAPTER 13. VACUUM PUMP

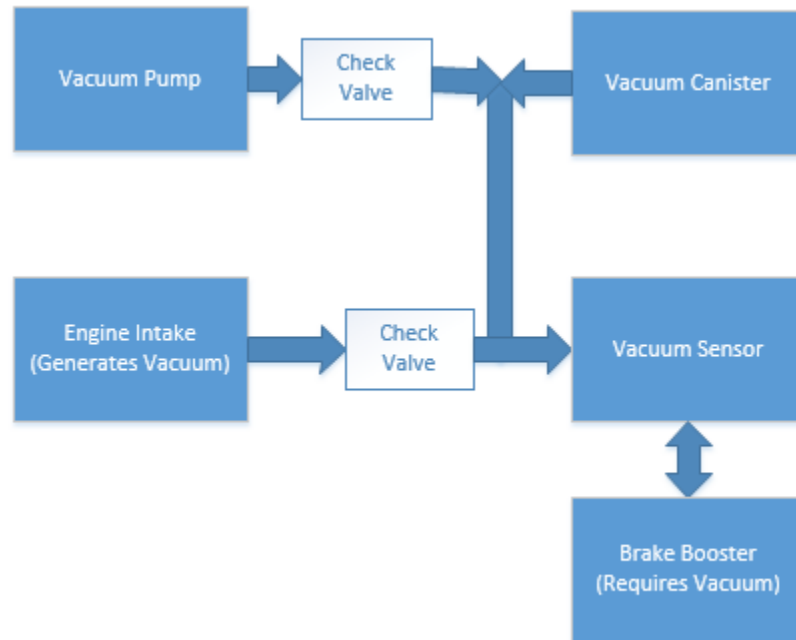
A vacuum pump is needed on a hybrid electric vehicle that supports an EV only mode because engine generated vacuum is often required for vehicle accessory systems, such as the braking system. When an engine is running, it functions like a large air pump, decreasing the pressure on the intake side and increasing the pressure on the exhaust side. Historically, many features have been run off the energy available in the vacuum system, such as transmissions, pop up headlights, or the hydraulic assisted braking system. In electrified vehicles, there has been a gradual transition away from the use of engine produced vacuum. That can be replaced by simply adding a vacuum pump that runs on the low voltage system, or removing the system entirely by replacing it with directly electrically powered systems such as in the Chevrolet Volt which uses an electric braking system. The team is using a Hella UP28 vacuum pump that is re-branded as an ACDelco part for General Motors shown in Figure 28.



**Figure 28: GM Vacuum Pump**

This pump was chosen because it could be purchased with GM blue dollars and provide a significant cash savings to our team. Blue dollars are credits each EcoCAR team receives that can be put towards the purchase of GM parts. An EV West vacuum pump switch was selected because it was simplistic and many individuals recommended using this switch. It operates in a thermostatic fashion. When the vacuum is too small it will supply the ground for a relay to turn the vacuum pump on. Once a high quantity of vacuum is built the ground

will be removed such that the relay will open and turn the vacuum pump off. A flow chart describing this full system can be seen in Figure 29.



**Figure 29: Vacuum System Diagram**

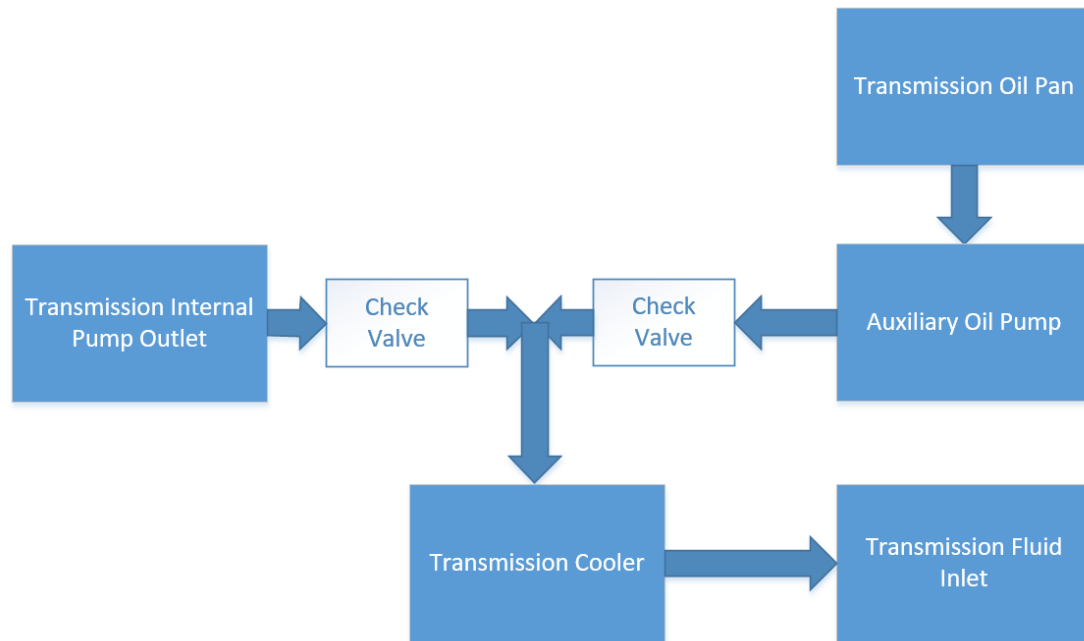
Initially, our team had many issues with this system because of vacuum leaks. In the presence of a vacuum leak, the switch will activate the relay, which causes the vacuum pump to oscillate on and off until the leak is resolved. If the vacuum leak is sufficiently large, the pump will stay on in a continuous attempt to establish a vacuum. An additional modification the team had to make was to smooth out casting imperfections in the pump switch to reduce the leakage. In this system, the brake vacuum pump is insufficient without the addition of a reservoir to increase the instantaneous vacuum output of the system. As a result, a vacuum reservoir was added inside the front driver side fender.

## CHAPTER 14. TRANSMISSION OIL PUMP

Different vehicle architectures require different precautions. This 2016 Camaro is capable of an electric only mode therefore precautions must be taken to ensure that the transmission is not damaged when the vehicle is being driven. Some vehicle architectures are designed such that there is a clutch between the transmission and driveshaft exiting the transmission so the transmission output shaft is not spun while the vehicle is in an electric-only mode, but this is not the case with the GT EcoCAR 3 Camaro.

In order for the vehicle to be driven in neutral, the transmission must be properly lubricated. In this vehicle, the transmission output shaft is rigidly connected to the differential through shafts in the transfer case. Inside the 8L45, the transmission lubrication pump is driven via the input shaft for the transmission. Typically, this is not an issue in Camaros because the engine, and thus the transmission input shaft, is always rotating when the vehicle is moving. However, this presents an issue for electric only driving because our rear traction motor only spins the transmission output shaft. In the event of a towing necessity, the rear wheels must not be rotated above 50mph in order to prevent driveline damage.

A solution to this problem is to add an auxiliary lubrication pump that can be activated when the vehicle is driving in electric only mode. As shown in Figure 30: , this pump was connected into the transmission pumping system with two check valves so the pump will not run unnecessarily, and so that the transmission's internal pump is still operable.



**Figure 30: Transmission Oil System**

After evaluating different options, the team ultimately selected Turbowerx Exa-Pump Mini shown in Figure 31: because it was the least expensive pump that met the requirements. Primarily, the team needed a reliable pump that could supply 6 liters of ATF per minute with the minimal amount of noise and cost possible. The primary contenders were the pump that was ultimately selected and a Tilton Buna oil cooler pump.



**Figure 31: Transmission Oil Pump [17]**

While these were all excellent options, the team sourced the Turbowerx pump at a significant student discount and the Turbowerx pump was expected to be significantly quieter based on previous experiences.

## CHAPTER 15. SUMMARY AND CONCLUSIONS

The goal of this thesis was to produce a document that describes the interactions between the major components within Georgia Tech's EcoCAR 3 vehicle. The interactions between major powertrain components were described and some justification was given to why the interconnections present today were selected. These major components also required supporting equipment that has been discussed.

If a team was starting from the inception of a vehicle development process this thesis would hopefully be beneficial in helping the team in the component selection and integration process. They could have some degree of confidence that the components discussed above could function in their vehicle development. Additionally, some of the pitfalls in the hybrid electric vehicle development process are discussed to help individuals or teams who intend to develop hybrid vehicles in the future.

As Douglas Cox's thesis served to give team members an understanding of what selection and development decisions were made in Year 1 and 2, this thesis accurately discusses the development in Year 3 from an electrical and controls interconnects perspective. This thesis also serves as a snapshot in time for the EcoCAR 3 vehicle development for new team members working on the vehicle through Year 4 of competition to understand what interconnects were made and why.

At the Year 3 competition the vehicle performed wonderfully, and the team's presentations were excellent to match. The team has a lot of work ahead of them, but they have already made strides toward success since I started this thesis.



## SCHEMATIC



### Figure 32: EcoCAR3 High Voltage Schematic

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